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Design and control optimisation of adaptive insulation systems for office buildings. Part 1: Adaptive technologies and simulation framework

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ABSTRACT

The increasing insulation levels imposed by building regulations have the effect of reducing heating energy use, while increasing cooling energy use and/or reducing thermal comfort especially in summer. Adaptive insulation technologies could provide an opportunity to reduce building energy use while simultaneously improving indoor environmental quality, but there is a lack of information about the performance of these novel technologies.

This paper is the first of a two part study, which aims to evaluate the performance of adaptive insulation. Part 1 proposes a simulation framework for optimising adaptive insulation design and control parameters and explains its implementation. The customised simulation strategy optimises design and control aspects of adaptive building envelopes by minimising the total primary energy use and thermal discomfort within a building. Moreover the simulation model for adaptive insulation is validated qualitatively. Part 2 applies this framework in a parametric study to explore the potential of adaptive insulation.

1. Introduction

The relatively high levels of energy consumed in buildings is of global concern. The stringent CO_2 emission targets imposed on the building sector by the 20-20-20 European policy, has stressed the importance of innovative technologies as a means of reducing energy use and CO_2 emissions in buildings, while maintaining high levels of indoor environmental quality (Energy Performance of Building Directive recast 2010/31/EU [1]). Meanwhile, the Chinese government has set a target that 50% of the newly constructed buildings should meet green building standards by 2020 [2], which should also be achieved by development and application of novel construction materials and systems, as recommended in China's 13th Five Year Plan for Housing and Urban Construction Planning [3]. The building envelope plays a key role in affecting energy use and environmental comfort [4]. In response to these ambitious targets, building regulations have traditionally focused on *reducing* heat and mass transfer through building envelopes through higher insulation levels and increased air tightness [5]. However, the objectives of energy saving and occupant comfort are sometimes contradicting. For example, in a temperate climate, a high thermal insulation is desirable in winter for reducing heat losses, but in mid-seasons and summer this could contribute to retain undesirable heat, causing overheating discomfort. This tends to occur in buildings with high solar gains (high amount of glazing with high solar transmission, unfavourable orientation) and/or high internal loads (e.g. office buildings), where summer thermal comfort could be sacrificed or more energy is required to maintain an acceptable thermal environment [6]. Building envelope technologies that are able to *modulate* the energy and mass transfer between a building and its external environment could address this transient conflict and help achieve future building energy efficiency targets [7,8]. The unique feature of these technologies is the capability to adjust their thermo-optical properties reversibly to transient boundary conditions (either external, such as climate, or internal, such as occupants' requirements), in response to changing priorities (i.e. minimising the building energy use, maximizing the use of natural light, etc.). Currently a wide range of technologies are available [9–15]. In particular, dynamic insulation is capable of modulating

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Nomenclature

λ	Thermal conductivity (W/mK)
U	Thermal conductance (W/m^{2}K)
R	Thermal resistance (m^{2}K/W)
η_h	HVAC efficiency for heating
ACH	Air change per hour
$T_{heating}$	Heating set point temperature
$T_{cooling}$	Cooling set point temperature
t	thickness (m)
κ_e	External thermal capacity (kJ/m^{2}K)
κ_i	Internal thermal capacity (kJ/m^{2}K)
FM	Frontal mass (kg/m^2)
D	Decrement Factor (−)
φ	Time lag (h)
R_{INS}	Thermal resistance of the adaptive insulation
MPC	Model predictive control
Pop	Optimal population size
Gen	Number of generation
PF	Pareto Front

the amount of heat transfer across the building envelope, admitting desirable heat gains while reducing unwanted heat losses in winter, or increasing the desired heat losses in summer while preventing unwanted heat gains. Therefore, the integration of dynamic insulation in the building envelope could enhance indoor thermal environment and simultaneously reduce energy demand in buildings.

The successful integration of adaptive insulation in building envelopes requires effective identification and assessment of the design parameters and control strategies to satisfy various design objectives simultaneously. Therefore, the purpose of this two-part paper is to evaluate the building performance improvements achievable by integrating adaptive insulation in opaque building envelope components, in terms of reducing the total primary energy use and the thermal discomfort. In this first paper the motivations and the simulation framework for the evaluations are presented, while in the second paper the methodology is applied to a case study in a temperate climate. In the second section of this first paper a comparative review of different adaptive insulation technologies and their control strategies is presented. Given the importance of building operations on the performance of adaptive building components, an overview of coupled design and control problems is provided in Section 3. In Section 4 a design and control optimisation framework for adaptive building envelope is proposed and described, together with its main implementation parameters. A qualitative validation of the adaptive insulation model is detailed in Section 5.

2. Adaptive insulation technologies

The earliest concept of dynamic insulation was introduced in windows systems [16,17] to prevent unwanted heat losses in winter, by introducing insulating materials in the window shutters. The operation of shutter-integrated insulation for windows was very limited, since it can be used only at night times for winter heat loss management. This was followed by a technology that integrates the facade with a system able to modulate heat convection through air [18] or liquid [19,20]. The former involves a cavity that pre-heats the fresh air before it comes into a room and reuse the heat from exhaust air by an air heat recovery system. However due to the high level of air-tightness and the heat recovery system required, this solution is not cost effective [21]. The latter, so called bi-directional thermodiode, is capable of enhancing the heat transfer in one direction by liquid flowing into a piping system across an insulating medium (forward mode), while providing insulation when the heat transfer is unwanted (backward mode). Different design variations of the bi-directional thermo-diode have been proposed and tested, the one developed by Varga et al. [22] for the cooling season achieved switchable apparent conductivity of 0.07 W/mK for the backward mode and 0.21–0.35 W/mK for the forward mode. In Pflug et al. [12] a dynamic insulation system is achieved by allowing or preventing convection between cavities in a multi-layered construction. This is achieved by movable panels in the construction element that allow/prevent natural convection between the cavities.

Adaptive insulation could also be achieved at a micro- or nano-scale by different strategies: variation of gas pressure, mean free path of the gas molecules and gas-surface interaction in an insulation panel. In a system patented by Xenophou [23] the thermal conductivity is modulated by controlling gas pressure in a wall with cellular structure. Another similar example is found in Benson et al. [24], in which a variable thermal transmittance is achieved by changing the pressure of hydrogen gas by means of absorption/desorption process of the gas itself. Berge et al. [25] developed a system to modulate the thermal conductivity of the air in the nano-porous fumed silica structure of a Vacuum Insulation Panel (VIP) or in an aerogel blanket, by controlling the air pressure by means of a vacuum pump. In Kimber et al. [26] the thermal transmittance of a wall is controlled by modulating the distance between multiple multi-layered polymeric membranes. Recently carbon nanotubes suspensions in liquid have been shown to provide a reversibly changing thermal conductivity that can be controlled by varying the direction of the nanotubes, modulated by a change in temperature of the material (phase transition at 18 °C) [27] or in the velocity of the fluid [28]. In these applications the thermal conductivity can be varied by a factor of 2–3 (from 0.4 to 1.2 W/mK). However in the current form these thermal conductivity values are too high for building insulation. Chandrasekhar et al. [29] presents the application of an electrochromic coating to control the emissivity of a surface for space craft applications, which can be actuated by electrical current. No more than 0.5 variation in the emissivity of a surface is achieved, so that its application on building surfaces would be limited, unless radiative heat exchange is the predominant heat exchange mechanism. The different adaptive insulation technological solutions for building application found in literature are compared in Fig. 1[1] and Table 1, in terms of the adaptive range of thermal conductivity (λ, W/mK), resistance of the construction element (*R-value*, m^{2}K/W), mechanisms to achieve the adaptive insulation, documented or tested control algorithm and speed to achieve the full adaptive range of insulation, where available.

A wide range of control strategies are adopted in literature to operate an adaptive insulation system (both in experimental and simulation studies). All these control strategies are based on control rules considering past and present states of the building and/or building envelope system (rule based control), such as occurrence of heating and cooling loads [25], difference between indoor and outdoor temperature [12], difference between wall surface temperature and indoor heating and cooling set-point [30,31]. Recent and more advanced control strategies present exciting opportunities for adaptive insulation by for example minimising a cost

[1] Note that a logarithmic scale is used in Fig. 1, in order to show all the results in the same graph. Reference to common construction material properties is represented.

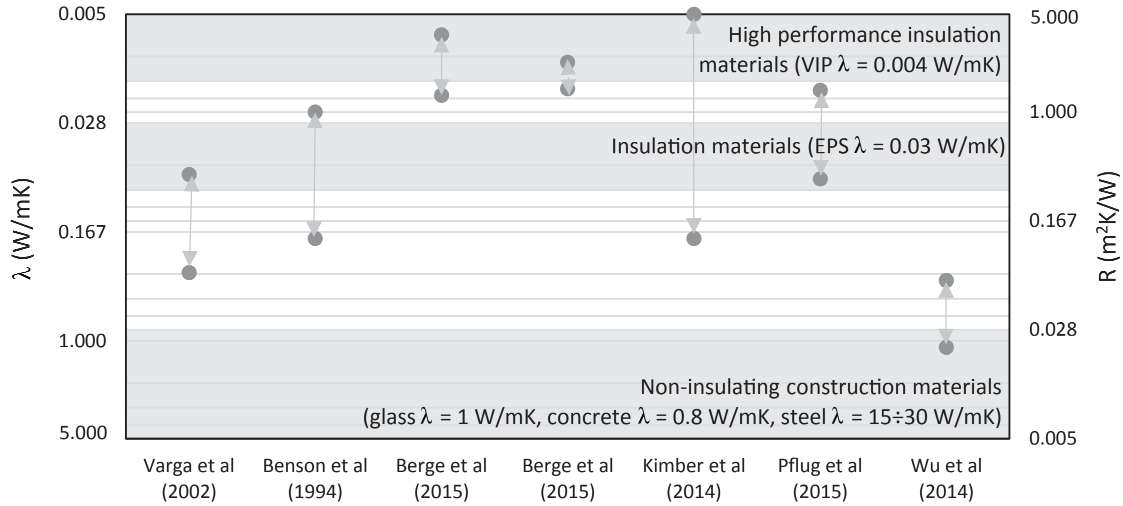

Fig. 1. Thermal conductivity (λ) and R-value modulation of adaptive insulation materials and technologies (y-axis with logarithmic scale). Where only one indicator is found in literature (i.e. only the U-value or only λ), the other one is calculated supposing a 0.025 m thickness of the insulation layer.

Table 1
Comparison of switchable insulation technologies based on the performance data available in the literature.

Reference	Description	Mechanism	λ (W/mK)		R (m^{2}K/W)		Control	Speed
			Min	Max	Min	max		
Varga et al., 2002 [22]	Bi-directional thermo diode	Convection	0.070	0.350	0.07[a]	0.36[a]	NA	NA
Benson et al., 1994 [24]	Variable conductance insulation	ab/de-sorption	0.025[a]	0.200[a]	0.13	1.00	NA	NA
Berge et al., 2015 [25]	Variable pressure VIP	Pressure	0.007	0.019	1.32[a]	3.57[a]	Demand	20 min
Berge et al., 2015 [25]	Variable Pressure Aerogel blanket	Pressure	0.011	0.017	1.47[a]	2.27[a]	Demand	20 min
Kimber et al., 2014 [26]	Adaptive Multilayer Wall	Air layer thickness	0.005[a,b]	0.200[a,b]	0.13[a,b]	5.00[a,b]	NA	Few mins
Pflug et al., 2015 [12]	Translucent element switchable U-value	Convection	0.0175″	0.075″	0.33	1.43	Temperature	Few mins
Wu et al., 2014 [27]	Carbon nanotubes suspension in liquid	Direction of nanotubes	0.400	1.200	0.02″	0.06[a]	NA	Few secs

[a] When only λ or *R-values* are given in literature, this value is calculated based on 0.025 m thickness of insulation layer.
[b] Kimber at al. 2014 [27] describes a prototype and a design method to achieve a target R-value, choosing the spacing, number of layers and emissivity, depending on the climate location. It should be noted that the R-value is only theoretical. The design parameters to achieve the adaptive insulation range are n = 20 (number of layers) and emissivity 0.01.

function (such as energy use and/or thermal discomfort) [32]. This control techniques are referred to as Model Predictive Control (MPC) or Receding Horizon Control (RHC) [32]. This is a feedback non-linear control technique, that solves an optimisation problem at each time step of the simulation/operation to determine the control sequence (sequence of optimal adaptive building envelope properties) over a certain time horizon (planning horizon), by minimising a specified objective function, which includes the prediction of the effect of varying material properties in the future states of the building system. Due to the delayed thermal inertia response of the building to a control action on the adaptive insulation, MPC could be particularly promising if adopted to control an adaptive insulation system.

The adoption of more advanced control strategies, such as having direct access to the principal performance indicators, being able to find a balanced multi-criteria trade-off point and incorporating the prediction of the effect of varying thermo-physical properties on the future energy balance of the building (receding horizon or model predictive control), may increase the performance improvement of the adaptive insulation systems.

There appears to be no published research that investigates the influence of control parameters strategy on the performance of an adaptive insulation system. In fact, the research works reviewed provide forms of building performance analysis limited to one specific technological solution, adopting a single specific control strategy. In addition, the possible mutual influence of the physical characteristics and the control of the dynamic insulation on the performance of the adaptive building envelope was overlooked in the studies to-date.

3. Design and control optimisation for adaptive building envelopes

Building performance simulation (BPS) has the potential to support building integration of adaptive façades and to enhance virtual rapid prototyping of novel building technologies, evaluating different design alternatives and exploring high-potential control strategies that maximise building performance [33]. Moreover, simulation of optimal control strategies, such as MPC, can provide an upper bound estimate for the performance of a building integrating an adaptive building envelope system, i.e. can evaluate the highest performance achievable by means of controlling the adaptive building envelope system. Performance evaluation of adaptive building envelopes, such as dynamic insulation, is a complex task for the following reasons [34]: i) unavailability of building simulation models for specific technologies; ii) influence over multiple interrelated physical domains; iii) mutual influence between optimal design characteristics (i.e. the physical characteristics and the modulation time range) of the adaptive technology and control aspects. Different researchers optimised alternatively either the control strategy of an adaptive building envelope technology, or the design characteristics of an adaptive façade.

Therefore, when control is optimised the design characteristics are predefined, or when design is optimised only an arbitrary control strategy is adopted. For example, Berge et al. [25] and Pflug et al. [12] performed a parametric study to improve the energy performance of a building integrating adaptive insulation by varying design parameters of the adaptive façade (i.e. minimum and/or maximum U-value achievable by the dynamic insulation wall), for a predetermined control strategy. In this case had an alternative control strategy been adopted, it would probably have resulted in a different set of optimal physical dynamic characteristics. Alternatively, as in Ref. [35–38], different control strategies with defined design characteristics (thermo-optical properties) were compared to optimised total building energy use and visual comfort. In the latter case the optimality of the control strategy identified in these studies are likely to be sub-optimal for alternative ranges and sets of design characteristics.

Some recent innovative approaches provide a first attempt to map the mutual influence between design and control aspects for adaptive facades (switchable glazing in this case). In Ref. [39], optimal design characteristics of switchable glazing (i.e. thermo-optical properties) were devised by receding horizon control to minimise total primary energy use. Alternatively, in Ref. [40] a two-step process was followed, first the performance of alternative control strategies was evaluated for a switchable glazing with average design characteristics (i.e. the thermo-optical properties) of the switchable glazing, subsequently the best control strategy according to one or more performance indicators was adopted to optimise the design characteristics.

Different cases of design and control optimisation are found for building energy systems. For example, Ashouri et al. [41] used a lumped-parameter model to optimise jointly building control and the design of the energy supply systems. Evins [42] used the same approach, adding deterministic model predictive control, to solve the control optimisation problem. The terminologies "Bi-level" [43], "Master-Slave" [44] and "Multi-level" [42] have been used to classify this kind of optimisation problems, as they combine design-level issues (upper level) with operational-level performance (lower-level) of the designed systems. In particular the upper level optimal results (optimal design characteristics) depend on the solutions of the lower level (optimal control alternatives).

4. Design and control optimisation framework for adaptive building envelope

For buildings with adaptive building envelope system, primary energy use can be minimized by controlling either design or control parameters to maintain a satisfactory level of indoor environmental quality. For example, this could be done by controlling design parameters such as the way heating, cooling and lighting energy is delivered or transformed by the building services, and/or controlling how the building energy demand is satisfied by a certain primary source; or by controlling the control strategies such as the way energy is transferred between the outdoor and indoor environment through the building envelope (heat, radiation and mass transfer). For these reasons, for an adaptive insulation system, methodologies in which the control and the design parameters are considered separately could lead to sub-optimal results.

In this paper a customised BPS framework is constructed to evaluate the potential of the integration of dynamic insulation in the building envelope considering this relationship between design-level aspects and operational-level performance, i.e., both design and control parameters are varied at the same time. The two levels considered are:

- Building design level: design variables of the dynamic insulation system, affecting primary building energy use and thermal comfort, such as minimum and maximum thermal resistance of the dynamic insulation, thermal capacity of the building envelope and relative position of the insulation compared to the thermal mass of the building envelope;
- Operational level: variables that determine how the adaptive building envelope system could be controlled during building operations. In the operational level possible building operation strategies are considered and simulated in order to support the development of an adaptive technology/product, although this may not correspond to the actual building operation strategy.

4.1. Framework description

The "bi-level" design and control optimisation framework for adaptive building envelope is shown in Fig. 2. The main purpose of the framework is to evaluate/optimise the performance of an adaptive building envelope components by varying both the design parameters and control strategies. The framework is divided into four layers, and each layer is described in terms of its functions, relationships, input parameters and software adopted for its implementation. Only the first two layers are used for building design level (rule based controls), and the last two layers are for operational level. The four layers are used in consequential order from 1 to 4, and the results of a lower level layer are passed to the upper one at the end of each evaluation/optimisation iteration. Details of the four layers are as follows:

Layer (1): Optimisation/Parametric Analysis. its functions are to: a) define the performance requirements to be evaluated/optimised; b) generate models with alternative design/control

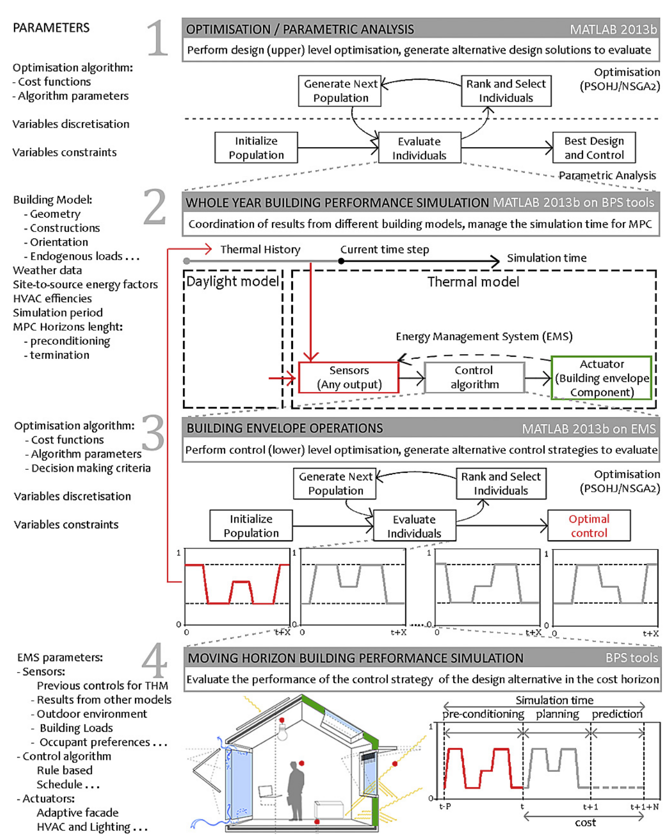

Fig. 2. Design and control optimisation framework for adaptive building envelope.

solutions to be evaluated by means of a whole year building performance simulation analysis; c) perform the design (upper) level optimisation/parametric analysis to evaluate the results from the whole year building performance simulation, based on the predefined performance objectives;

Layer (2): Whole Year Building Performance Simulation. its main functions are, for each model generated by layer 1, to: a) if rule based control is performed, run the building performance simulation for the whole year; b) if Model Predictive Control (MPC) is performed, integrate the results from subsequent time-steps and move the simulation horizon from the start to the end of the simulation period (examples of rule base control and MPC are shown in Section 2.1 in Part 2);

Layer (3): Building Envelope Operations optimisation. its main functions are to: a) generate alternative control sequences for the planning horizon to be passed to the lower layer (4); b) perform control (lower) level optimisation analysing the results based on the building performance simulation analysis in the lower layer (4) for the cost horizon, based on the performance objectives defined;

Layer (4): Moving Horizon Building Performance Simulation. its main function is to evaluate the building performance of each control strategy (defined in layer 3) of a certain adaptive building envelope component, by performing the simulation on each simulation horizon (defined in layer 2). The length of the simulation horizon and how it is defined is described in the next section.

The performance of each specific control sequence (defined in layer 3) of a design alternative (defined in layer 1), is evaluated by layer 4, and the results passed to layer 3. Once the control sequence is optimised by layer 3, the control sequence for the planning horizon is passed to layer 2 which moves the simulation horizon for the time corresponding to the frequency of control action. This loop is repeated until the end of the simulation period (year) is reached by layer 2, and the yearly results are passed to layer 1. This generates the next design alternative to evaluate and the whole process continues until all design alternatives are evaluated (for parametric evaluation), or convergence is reached (for optimisation) in layer 1.

Different building performance simulation tools, depending on the kind of performance characteristics that is being evaluated, and optimisation software could be integrated at each level. In the present study MatLab [45] is used to coordinate the different simulation layers and to perform the parametric analysis in layer 1 and the optimisation in layer 3 by means of NSGA II algorithm [46]. The use of reduced order building models for control optimisation does not allow complex heat and mass transfer phenomena to be studied [40], i.e. non constant material properties and heat storage phenomena. In contrast the use of complex modelling tools, although computationally expensive, allows the designer to optimise the control strategy of an adaptive façade, taking into account all complex heat, radiation and mass transfer phenomena properties of adaptive facades. For these reasons EnergyPlus [47] is adopted to evaluate the building performance, moreover its capability to be executed as a console application from the “command window” and the text file input models and output results, makes it easier to interface with the optimisation scripts in Matlab. The simulation parameters in EnergyPlus were chosen (solar calculations 15 days, conduction transfer function method with a 10-min time step, adaptive convection algorithm, initialization period = 25 days) to achieve a balance between accuracy and a reasonable computational time of a single simulation run. Within EnergyPlus the adaptive insulation was simulated adopting the “SurfaceControl:MovableInsulation” class list [44]. Additional information about the EnergyPlus adaptive insulation model and its reliability are provided in Section 5.

4.2. Parameters for the implementation of the simulation framework

4.2.1. Performance objectives

The main purpose of the simulation framework is to evaluate and/or optimise a certain building design and/or control alternative based on one or more user defined performance objectives, i.e. total primary energy use, thermal comfort, visual comfort etc. If control and/or design optimisation is performed, either single or multi-objective optimisation can be adopted according to the number of performance objectives considered.

4.2.2. Time horizons and thermal history management

The simulation of an optimised control, i.e. MPC, involves solving an optimisation problem for time horizons which are smaller than the total simulation time (one year). This time horizon is called cost horizon, it involves a planning horizon for which the control strategy has to be planned and a termination horizon, to take into account the effect of varying material properties on the building energy balance after the planning horizon. A planning horizon of one day is considered, in which a sequence of control actions need to be optimised (for example 24 possible actions if the adaptive insulation can be controlled on an hourly basis). Two days termination horizon is adopted to take into account weekend dynamics, as suggested by Corbin et al. [41]. In order to achieve the full benefits of MPC control the total cost horizon should generally be no shorter than three times the time constant of the building or three times the planning horizon [48]. In EnergyPlus when one optimisation is completed and the simulation is moved one control action forward in time, it is not possible to explicitly set the starting boundary conditions for that subsequent optimisation (such as surface and material temperatures) as the ending conditions of the previous one. The Thermal History Management technique (THM) [41] could be used to address this issue, and it is implemented for the case of adaptive building envelope as detailed in Refs. [49] and [38], consisting of re-simulating the building for a certain number of days (pre-conditioning horizon) with previously optimised control, in order to reach the desired starting boundary conditions at each optimisation. The optimal length of the pre-conditioning horizon can be determined by means of a parametric study in order to quantify the influence of the length of pre-conditioning. In order to overcome specific limitation of EnergyPlus at simulating advanced control strategies [35], update the thermal history of the building model between subsequent optimisations [40] and compute the performance indicators from EnergyPlus outputs, the EMS tool is adopted within EnergyPlus [58]. The implementation and the simulation workflow of the MPC (control optimisation, involving layers 2 to 4) is detailed in previous publications [42,49,59].

4.2.3. Population size and number of generation

NSGA II algorithm [50] is adopted to solve multi-objective optimisation problems. A convergence test should be carried out to find the optimal population size and number of generations for the optimisation analysis.

4.2.4. Multi-objective decision making approach

If more than one performance objective is adopted to evaluate or optimise the design parameters and control strategies, for each planning horizon (1 day) a Pareto Front (PF) is generated by the NSGA II, i.e. according to the definition of PF (or non-domination) one objective can only be improved at the expense of the others. In order to move the simulation time forward and operate the adaptive component accordingly, one control solution of those found in the PF must be selected. Alternative approaches are available in literature for decision making in multi-objective optimisation. Marler and Arora [51] classified them referring to the sequence of the decision making with the optimisation task into "a-posteriori", "a-priori" and "no-articulation" of preferences. In the absence of a decision maker, when the process is automated, only the last two methods can be used. In the a-priori methods preferences, which may be articulated in terms of goals or of the relative importance of different objectives, need to be defined prior to simulation. The way to articulate them is to define a utility function, which sums up in a single objective the different objectives, by means of weighting coefficients and/or constraints. An example of the first approach is found in Jin and Overend [2], who incorporated in a single Indoor Environmental Quality (IEQ) objective thermal, visual and air quality objectives first, and then summed up energy savings and Indoor Environmental Quality by means of their economic value. This approach relies on a-priori definition of relative importance of the different objectives, which is not always possible.

If no information about the occupants' preferences exist about how an adaptive façade should be controlled, when deciding for example between the relative importance of thermal comfort and energy use, the "no-articulation" approach is more suitable. Among the methods with no-articulation of preferences, the TOPSIS approach (Technique for Order Preference by Similarity to the Ideal Solution) [52] simultaneously takes into consideration both objective function values while avoiding the rank-conflicting dilemma. This was adopted in Ref. [53] and compared to a-priori articulation of preferences methods, in order to benchmark building performance according to different indicators (among the others Energy Use Intensity, Cooling, Heating and Total degree day efficiencies). As shown in Fig. 3, with this approach two ideal solutions (Ideal best, I_B, and Ideal worst, I_W, with mixed coordinates of the two best points according to the contrasting objectives, C and D) are identified, and the normalized relative distance from these two solutions is calculated for each point in the PF (for example data points A, B). The solution closer to the ideal one is then chosen, data point A, which is the best one for multi-objective optimisation according to the TOPSIS approach, while data point C is the best solution as far as energy use is concerned and D is the best one as far as thermal comfort is concerned. This approach is adopted in the simulations in this paper. In Section 2.3.3 of Part 2, a parametric analysis to assess the effect of the TOPSIS approach against single objective optimisation criteria, such as minimising energy use only or global thermal discomfort, will be provided. By means of the TOPSIS approach a significant reduction of both total energy use and thermal discomfort is achieved simultaneously, even if a higher

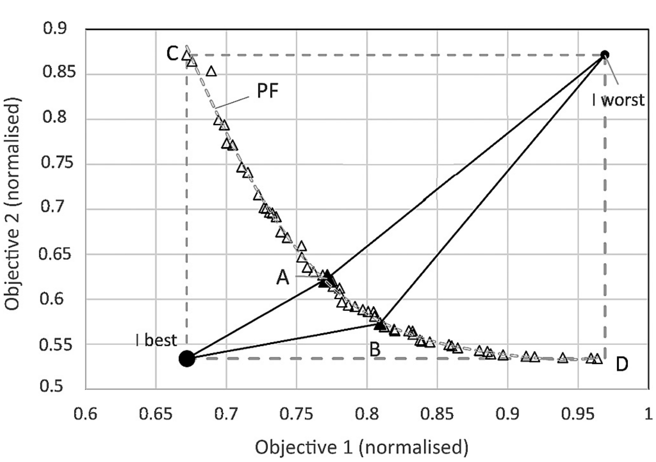

Fig. 3. Pareto Front for the control optimisation of an adaptive insulation.

performance could be achieved as far as each individual objective is considered.

It is possible that for some specific planning horizon the two performance requirements are in agreement, i.e. minimal energy use corresponds to maximum thermal comfort. This can happen for example in extreme climate conditions, e.g. very cold and cloudy days in winter and very hot and sunny days in summer. In this case no trade-off is needed between control solutions, and the best control solutions found by means of the TOPSIS approach are identical to those found by any other approach for multi- and single-objective optimisation.

5. Simulation of adaptive insulation and qualitative model validation

The "SurfaceControl:MovableInsulation" class list [47] was adopted within EnergyPlus to simulate the adaptive insulation. In this class list, the value of the thermal resistance of a massless insulation layer can be modulated by defining a fractional schedule (values between 0.0, null thermal resistance, to 1.0, entire thermal resistance of the insulation available), which is a multiplier of the thermal resistance of the adaptive insulation layer. In order to verify the reliability of simulating the adaptive insulation as a massless layer a brief model comparison was carried out using a building test case model.

5.1. Building test case model

A cellular office room in Shanghai (Fig. 4) is adopted. This model was adapted from an experimentally validated model of a climatic chamber [54]. The room size is 4 m high × 4.5 m wide × 3 m deep. All the internal surfaces are assumed to be adiabatic, apart from the south façade. This represents an office room surrounded by office rooms with identical indoor environment and occupation in a multi-storey office building.

The external facade is partially glazed (window-to-wall ratio WWR = 60%) with a highly transparent triple glazing (U-value = 1.1 W/m^{2}K, g-value = 0.62, visible transmittance = 0.79). Horizontal Louvers with medium reflectivity slats (0.5 reflectivity) are placed on the exterior part of the glazed façade, and the slat angle adjusted to block direct solar radiation. The aspect ratio for the office room (façade to floor area) is 1:1 (Fig. 4), representing the office in the perimeter area (except the corner) of the building.

The main building parameters are derived from local design standards for energy efficient buildings [55], such as: endogenous loads consisting of 2 occupants, 18 W/m^2 of lighting power density, 13 W/m^2 for equipment power density; 5 m^3/hm^2 for façade permeability at 50 Pa differential pressure; 20 °C heating system set point, with 13 °C nocturnal setback (10 p.m.–6 a.m.); 25 °C cooling system set point, with 30 °C nocturnal setback (10 p.m.–6 a.m.); HVAC efficiency for heating η_h is 0.89 and the seasonal energy efficiency ratio (SEER) for cooling is 3.8; automated continuous dimming control for artificial lighting (illuminance set point 500 lux, reference points at mid-point room depth, height 0.8 m). While

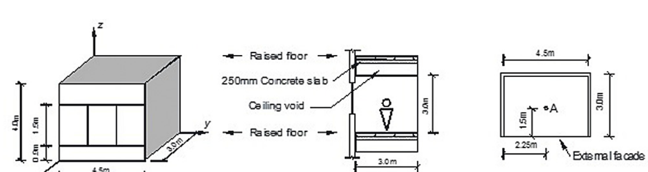

Fig. 4. Enclosed office room model.

schedules for endogenous loads are derived from ANSI/ASHRAE/IES [56]. Primary ventilation of 1.4 l/sm^2 is provided when the office is occupied, when heating loads are present and throughout the day during the cooling season, which corresponds approximately to 2 ACH. The sensitivity of building energy use to the ventilation rate was previously verified, in order to assess the potential of free ventilative cooling in the summer period as a passive design strategy alternative to adaptive insulation. Air changes in excess of 2 per hour, which is the minimum requirement from local regulation [55], during occupied and unoccupied office hours, were found to be ineffective for decreasing primary energy use during the summer period.

It is assumed that the opaque portion of the façade is constructed as shown in Fig. 5, i.e., the insulation layer (R-value = 5 m^2 K/W) is wholly on the external side of the thermal mass layer. Detailed properties are listed in Table 2. This design configuration was chosen because a) it is one of the best performing design alternatives (for static and adaptive insulation) as far as both total energy use and thermal comfort are concerned, b) it is the one with the highest sensitivity of performance indicators on the amount of insulation (c.f. Part 2 of this paper), c) the insulation is exposed to the most variable boundary conditions (external climate). The insulation layer can be either a conventional "static" insulation, or be actively controlled according to a specific control strategy. In particular, the insulation can switch from its maximum value (from Table 2) to its minimum value (no insulation at all), corresponding to a value of 1 or 0 respectively.

5.2. Simulation and model validation

The adaptive insulation is modelled with the "SurfaceControl:MovableInsulation" class list in EnergyPlus, and the static insulating material with the same resistance of the adaptive insulation layer (average density of 50 kg/m^3) is also modelled. The main purpose of this analysis was to compare the temperatures at the interface between the insulation layer and the concrete, and along the concrete layer, for the two cases. In particular, the temperature at different thicknesses along the building envelope were compared (outdoor air, external surface, insulation layer, interface surface between Insulation and concrete layer, at 4 points along the thickness of the concrete layer, and internal surface), for a typical sunny winter day (low temperature and high solar radiation) and a typical summer sunny day (high temperature and solar radiation). For the "SurfaceControl:MovableInsulation" class list, the adaptive insulation was set to 0 (no insulation present) between 10:00 a.m. and 4:00 p.m. in the winter case, and between 7:00 p.m. and 4:00 a.m. for the summer case. The results of this comparison are shown for the winter case in Fig. 6 and for the summer case in Fig. 7.

In winter (Fig. 6) when a static insulation is present the outdoor surface temperature (S_out) rises (at 10:00 a.m. is about 50 °C) due

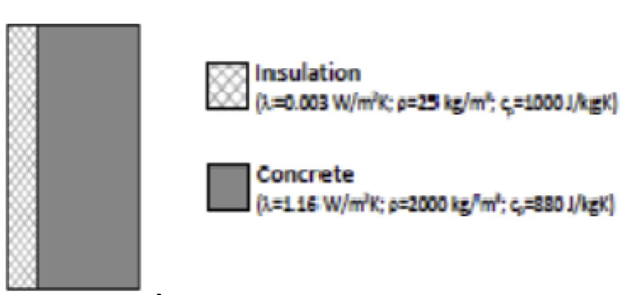

Fig. 5. Opaque wall construction.

Table 2
Opaque wall properties.

	Units	Value
t	M	0.23
U	W/m^{2}K	0.19
R	m^{2}K/W	5.34
κ_e	kJ/m^{2}K	3.00
κ_i	kJ/m^{2}K	73.00
FM	kg/m^2	401.00
d	–	0.20
φ	H	7.72

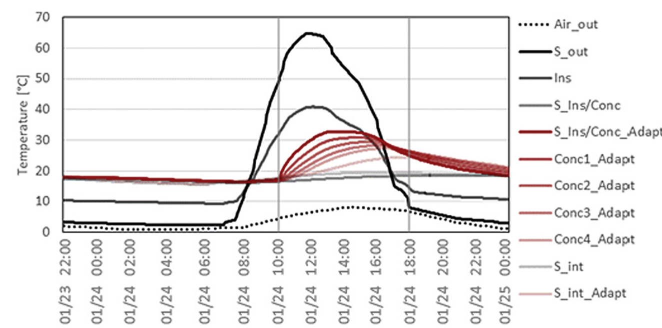

Fig. 6. Temperature variation along construction thickness for static insulation construction modelled with EnergyPlus building envelope model and adaptive insulation modelled with EnergyPlus "SurfaceControl:MovableInsulation" class list for winter case.

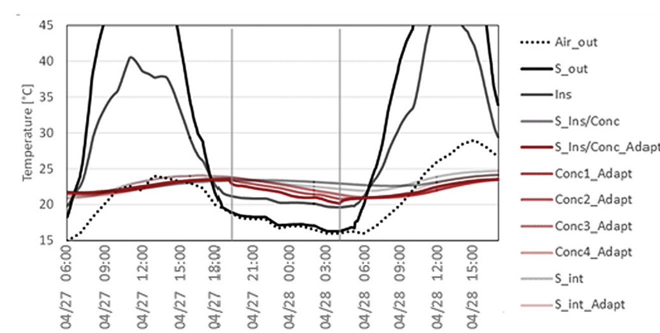

Fig. 7. Temperature variation along construction thickness for static insulation construction modelled with EnergyPlus building envelope model and adaptive insulation modelled with EnergyPlus "SurfaceControl:MovableInsulation" class list for summer case.

to the absorbed solar radiation (at 10:00 a.m. is about 300 W/m^2), but this temperature amplitude is decreased along the construction thickness due to the presence of the insulation (at 10:00 a.m. is about 32 °C in the insulation material, Ins, and 17 °C in the interface between the insulation and the concrete layer, S_Ins/Conc), while for the effect of the insulation material a very small temperature amplitude is transmitted to the internal surface (S_int). In contrast when the adaptive insulation is adopted, the temperature of the interface between the adaptive insulation and the concrete layer (S_Ins/Conc_adapt) is maintained the same as the static case (S_Ins/Conc) until 10:00 a.m., when the adaptive insulation is switched off, and it starts rising due to the effect of the absorbed solar radiation at the interface between the insulation and the concrete (at 10:00 a.m. Sun_ab_adapt equals the 300 W/m>^{2}). This temperature rise is reflected with a certain delay in the depth of the concrete layer (Conc1_adapt to Conc4_adapt curves in Fig. 6), and the peak internal temperature (S_int_Adapt) is measured 4 h later than the peak interface temperature between adaptive insulation and concrete (S_Ins/Conc_adapt). Due to an increased internal surface temperature for the effect of the absorbed solar energy, the use of the adaptive insulation in winter can increase the solar heat gains and therefore reduce heating energy while increasing the internal surface temperatures and the indoor thermal comfort. It is important to note that at 10:00 a.m. (when the adaptive insulation layer is switched off), the interface temperature between the insulation and the concrete in the two cases (static insulation modelled with EnergyPlus construction and adaptive insulation modelled with the "SurfaceControl:MovableInsulation" class list) coincide, as well as the absorbed solar radiation.

In summer (Fig. 7), during the day, when the insulation is present in both cases (static insulation and adaptive insulation) the outdoor surface temperatures (S_out), the internal surface temperatures (S_int and S_int_adapt), and the temperatures at the interface between insulation and concrete (S_Ins/Conc and S_Ins/Conc_adapt) coincide until 7:00 p.m. When the adaptive insulation is switched off during night the interface temperature between the insulation and the concrete starts decreasing, until a peak difference compared to the static insulation at 4:00 a.m. of about 3 °C, when the adaptive insulation is switched on again. This difference results in higher conduction losses through the building envelope during night and lower internal surface temperature for the adaptive insulation case (S_int_Adapt), compared to the static case (S_int) during the day, with the effect of reducing the energy use for cooling and the risk of overheating in the indoor environment.

The comparison between these two models allowed to understand the advantages of adopting an adaptive insulation in winter and summer as far as energy and thermal comfort are concerned, but also to verify the reliability of modelling the adaptive insulation as a massless layer with the "SurfaceControl:MovableInsulation" class list within EnergyPlus. Although this model comparison relies on the accuracy of the EnergyPlus building envelope model, which is documented in Ref. [60], while in order to comprehensively assess the accuracy of the "SurfaceControl:MovableInsulation" class list modelling method, a complete validation study is needed to compare the calculated and measured temperatures along a construction with an adaptive insulation layer.

6. Conclusions

Adaptive insulation has the potential to reduce building energy use and simultaneously improve occupant comfort, but its performance is not yet thoroughly understood. To overcome the intrinsic limitations of building performance simulations at simulating adaptive facades and their advanced controls, a bespoke methodology and simulation strategy is developed in this paper. The proposed design and control optimisation framework for adaptive building envelope follows a "bi-level" approach, which considers the interdependent variation of both design and control parameters simultaneously, and provides an accurate means of evaluating the effects of optimal control for adaptive insulation properties. Additionally, prior to parametric analysis/optimisation the adaptive insulation simulation model based on EnergyPlus is qualitatively validated. This also helps understand the behavior and performance of adaptive insulation in winter and summer in terms of reducing energy use and improving thermal comfort. In part two of this paper, this simulation framework will be adopted to evaluate the potential performance improvements of adaptive opaque insulation systems integrated in the façade of an office building in a temperate climate.

The simulation framework can also be potentially used to support the product development of adaptive building envelope systems and controls, as for example in the design and control of smart glazing systems, as documented in Ref. [38,39].

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